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Investigating the Influence of Handedness on EMG Movement Features – A Frequency-Based Analysis

Varun Jain
400183083
jainv8@mcmaster.ca

Principal Investigator (PI): Dr. Aimee J. Nelson, PhD
Local Principal Investigator (LPI): Dr. Aimee J. Nelson, PhD
Lead Student Co-Investigator: Stephen Toepp, PhD Student
Student Co-Investigator(s): Stevie Foglia, PhD Candidate, Ravjot Rehsi, MSc Student, Elizabeth Hofer, MSc Student, Varun Jain, BHSc Student, Tiffany Leung, BEng Student
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Introduction

Most individuals possess a tendency to prefer the use of a select hand while participating in certain activities or movements; this tendency is defined as handedness [1]. It has been observed within literature that handedness has led to asymmetry in the motor cortex as well as in some cervical spinal pathways, however, the effect of handedness in muscle activation patters recorded using surface electromyography (sEMG) has not been investigated in detail. Previously, Diederichsen et al. investigated handedness in human shoulder muscles during movement for which they were able to determine differences in EMG activity between the arms for specific muscles during abduction and external rotation [2]. Although significant results were determined, the movements were limited and the arms were supported by an armrest, which could have impacted the replicability of this study [2]. This is supported by the fact that many of the EMG movement features did not match those previously investigated by Beukelaar et al. in their dominant arm task [2,3]. Given the limitations in design as well as the narrow focus on shoulder muscles, an in-depth investigation on the effect of handedness across other muscular sites is prompted. In addition to broadening the muscular sites used in the testing protocol, including more functionally relevant movements (reach-to-grasp tasks) would adopt a novel approach in assessing EMG feature differences. These movements are performed on a daily basis by most humans outside of a laboratory testing environment, and thus would improve the generalizability and clinical usefulness of the results.

Through determining the effect of handedness on EMG movement features in functionally important movements, one would be able to improve the design of prosthetic and other assistive devices that rely on EMG features for control and movement. Specifically, it would include an added measure of control such that movements conducted by the device have limited error and require minimal tuning / optimization. Additionally, knowledge of the impact of handedness on EMG movement features can allow these features to capture more individualized movement control strategies and improve its accuracy in showcasing changes in EMG features over time.

For this study, a frequency-based approach was selected as it easily allows for differences in biomedical signals to be easily observed, as employed statistical tests compare the amplitude at a specific frequency between hands for a given movement. Comparing differences in frequency domain also allow for a more in-depth analysis in determining the factors that create a higher amplitude signal as these factors are not isolated within the time domain. This can be specifically applied towards noise or ECG artefacts that could be potentially present within the EMG signal [4]. Lastly, comparing signals temporally for repetitive movements could result in the identification of false positives; for example, human delay would be determined as creating a significant difference temporally, but its impact would be negligible in the frequency domain.

Determining the effect of handedness on the frequency of EMG movement features is clinically important in the design of prosthetic and other assistive devices, and it is also a critical avenue of research within rehabilitation studies. Therefore, the goal of the study is to investigate how handedness influences EMG movement features during dominant and

non-dominant limb movements in a healthy young right-handed male through a frequency-based approach.

Proposed Outcomes

The EMG movement features were evaluated using a two-way ANOVA and computing the F-statistic as well as the corrected p-value as per the Bonferroni-Holm correction post-hoc test. The purpose of the ANOVA was to evaluate whether differences were observed between limbs, sessions or whether these independent variables had an interaction effect on the EMG signal. In order to employ these statistical tests, MATLAB was used.

Participant Dataset

A young right-handed male graduate student (20-25 years) was recruited as the sole participant for this study. To be eligible for this study, the participant must have been between the age of 18 and 40 years, or older than 59 years. Additionally, they must not have had any stable or unstable medical condition or suffered a limb injury affecting the neuromuscular system in the past 12 months. Lastly, they must be able to perform all movements as described in the methods with a reasonable range of motion without any pain or discomfort. The recruited participant successfully satisfies all the eligibility criteria. Two testing sessions were performed, resulting in completed EMG dataset which was used throughout this study. The participant was provided with the study consent form and provided the researchers with a signed informed written consent form.

Methodology

The enrolled participant performed two EMG testing sessions within the laboratory separated by approximately 48 hours. Each session lasted between 2 to 3 hours. The timeline of sessions is provided in figure 1 below.

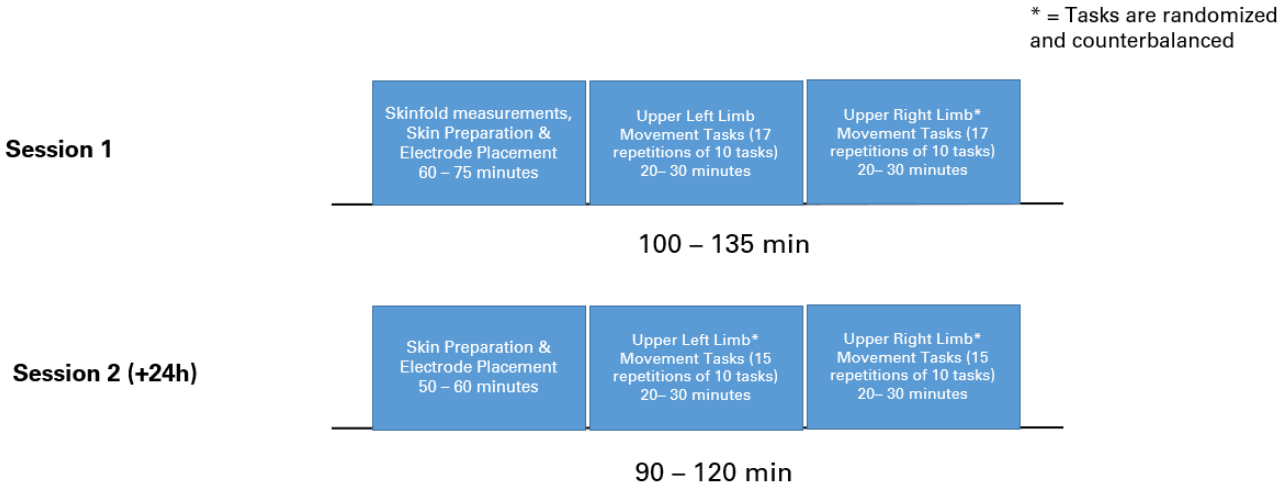

Figure 1: Timeline of EMG sessions

Participant Positioning

While conducting measurements for the electrode placement and baseline characteristics, the participant was seated in a comfortable position on the testing chair. For the movement tasks, the participant was seated upright in the testing chair with arms unsupported (i.e., no armrests) and hanging to the sides in a relaxed posture with fingers pointing towards the floor and palms facing medial.

Skinfold Measurements

Three skinfold measurements were performed bilaterally at each of the 2 sites on the upper limb using a caliper. The biceps skinfold measurement was performed halfway between the anterior auxiliary fold and the antecubital fossa and the triceps skinfold was obtained at the posterior midpoint of the upper arm between the acromion olecranon processes. The mean of the two closest skinfold measurement were taken at each site.

Skin Preparation and Electrode Placement

After performing the skinfold measurements, the participant's skin would be prepared. Skin preparation included shaving (only for the HD-EMG) and lightly abrading the skin over the muscles of interest and then wiping the with isopropyl alcohol. Muscles of interest include abductor pollicis brevis (APB), first dorsal interosseous (FDI), flexor carpi radialis (FCR), extensor carpi radialis (ECR), extensor digitorum superficialis (EDS), biceps brachii (BB), triceps brachii (TB), and middle deltoid (MD). Muscles of interest were identified by using measurements and practices outlined by the SENIAM guidelines. An area of the skin

on the medial aspect of the forearm was also prepared for the placement of a 7 cm by 7 cm high-density EMG grid (TMSi ltd. Oldenzaal, Netherlands) at the midpoint between the olecranon and styloid processes of the ulna. Prior to placing the EMG electrodes, the skin impedance was determined using a Model 1089 MK III Checktrode impedance meter (UFI, California, United States). If the recorded impedance was lower than 10kOhm, then the muscle of interest was appropriately prepared. Once all muscles of interest recorded an impedance lower than the 10kOhm threshold, EMG electrode placement commenced. Pre-gelled Ag/AgCl surface EMG electrodes were placed over the individual muscles, and the 64 wells of the 8x8 high-density EMG grid was filled with conductive gel (SONOGEL, Elektroden) before it adhered to the skin by a double-sided adhesive tape. Following electrode placement, pictures were to facilitate duplication of the electrode placement between sessions. This process took approximately 20 to 30 minutes per arm.

Upper Limb Movements

The participant performed six “isolated” movement tasks and four “reach-to-grasp” movement tasks which were performed by each arm at a pace of 50bpm for 43 seconds. Each movement task was comprised of two phases: the movement 1) from the start position to the end position, and 2) from the end position back to the start position. The participant was prompted to perform the movement after the third metronome beat. Additionally, the participant was informed to perform tasks repeatedly for the entire 43 second duration. After a movement task, the participant was given a 30 second resting period. The isolated movement tasks are outlined in Table 1.

Independent Movement(s)	Instructions
Shoulder forward flexion (phase 1/phase 2)	Start with arm relaxed hanging at the side of the testing chair. Raise arm anteriorly to eye-level without flexing or extending the elbow (1), and then return to starting position (2).
Elbow flexion/extension	Start with arm relaxed hanging at the side of the testing chair. flex elbow to 45° (1) and then extend back to the starting position (2).
Wrist extension/flexion	Start with the elbow flexed at 90° with the wrist fully extended. Keeping fingers relaxed, move the wrist into full flexion (1) and then back into full extension (2).
Ulnar/radial deviation	Start with the elbow flexed at 90° with the wrist in full ulnar deviation. Keeping the fingers relaxed, move the wrist into full radial deviation (1) and then back into full ulnar deviation (2).
Wrist supination/pronation	Start with the elbow flexed at 90° with the forearm rotated so that the palm of the hand faces upward. Keeping the hand relaxed, rotate (pronate) the forearm so that the palm faces downward (1), then rotate the forearm back to the staring position (2).
Hand opening/closing	Start with the elbow flexed at 90° with the hand opened so that the palm faces medial the thumb faced upwards (as if preparing for a handshake). Close the hand into a fist (1) and then open the hand, returning to the start position (2).

Table 1: Simple Movements and Instructions

The reach-to-grasp targets were placed in front of the participant's shoulder at 0.75 x the length of the arm (tip of the middle finger to the acromion process). Each target was fixed to the surface of a table and adjusted such that it is at normal desk height (77cm). For the horizontal and vertical handle grip tasks, a specific point on the handle was identified for the participant with tape to ensure consistency between repetitions. The four reach-to grasp movements are outlined in Table 2.

Independent Movement(s)	Instructions
Vertical handle grip	Start with arm relaxed hanging at the side of the testing chair with palm facing medial. Reach and grasp a vertical cylindrical handle (1), then return to the starting position (2).
Horizontal handle grip	Start with arm relaxed hanging at the side of the testing chair with palm facing medial. Reach and grasp a horizontal cylindrical handle (1), then return to the starting position (2).
Precision grip	Start with arm relaxed hanging at the side of the testing chair with palm facing medial. Reach and grip a small marble (1 cm diameter) between the thumb and index finger (1), then return to the starting position (2).
Cup grip	Start with arm relaxed hanging at the side of the testing chair with palm facing medial. Reach and grasp a rigid plastic cup (1), then return to the starting position (2).

Table 2: Reach to Grasp movements and Instructions

Prior to obtaining the EMG signal, the order of the movements were randomized using a random number generator function in MATLAB (MathWorks, Natick, United States). The randomized order stayed consistent between visits. Recording the EMG signal for all movement tasks took approximately take 20-to-30 minutes per limb, for a total of 40-to-60 minutes.

EMG Movement Features

The EMG signal was recorded using a TMSi SAGA 34/64+ device (TMSi ltd. Oldenzaal, Netherlands). After the recording session, all EMG data was filtered using a bandpass filter with a pass band between 10 Hz and 500 Hz (2nd order, Butterworth filter). The data for each movement was then segmented into its two phases based on cyclic peaks in acceleration recorded using a three- axis accelerometer (TMSi ltd. Oldenzaal, Netherlands), and researcher-chosen EMG validation channels. Specifically, a wavelet was developed such that the sum of differences was calculated for each movement. A local minima within the wavelet indicated the beginning of a movement. After segmenting the data, the independent movements were determined as seen in Table 1 and Table 2. To facilitate clear identification of movement phases, the accelerometer was attached to the middle phalanx of the fourth digit.

For the purpose of this study, the middle seven intervals were assessed for each of the listed movements in Tables 1 & 2. This was done to ensure that the effects of fatigue or unfamiliarity with the movement did not play a large role in the analysis of the data.

Statistical Analyses

The EMG data was analyzed by calculating the F-statistic from the mean frequency observed in each of the seven intervals. To compute the F-statistic, the data was first

converted to frequency domain using a fast Fourier transform (FFT). Afterwards, the amplitude data was filtered using a bandpass filter with a bandwidth of 20 to 500 Hz [5]. The bandwidth was determined based off of a study by Basmajian et al., who reported that the bandwidth of usable energy for sEMG signals is between 20-500Hz [5]. The data was filtered once again because upon visual analysis, the FFT showed a prominent peak at 0Hz indicating DC offset. After filtering the amplitude data, the mean frequency was obtained for all seven intervals and appended to an array for each of the validation EMG sites for each movement. To determine what statistical testing could be used, a Jarque-Bera test was performed to test for normality. The null hypothesis is that the data comes from a normal distribution and the alternate hypothesis is that the data does not come from a normal distribution. The Jarque-Bera test confirmed that all of the arrays appeared to have data representative of a normal distribution. Therefore, a two-way ANOVA was an appropriate statistical test for this dataset. The null hypotheses of the ANOVA are that there is no difference in mean frequency for each of the limbs, there is no difference in mean frequency for each of the sessions, and the effect of one independent variable on the mean frequency is not dependent on the effect of the other independent variable (no interaction effect). Prior to conducting the ANOVA, the data was manipulated such that a matrix was formed. The columns represented the upper limb conducting the movement (Left or Right), and the rows represented the different testing sessions (Visit 1 and Visit 2). Within the rows, there were seven replicates which represent the seven intervals from which the mean frequency was obtained. The resultant matrix was a 2x14 double, which was used in each of the ANOVAs. With each ANOVA, a Bonferroni-Holm correction post-hoc test was employed to control the probability of false rejections and to correct the calculated p-value accordingly [6]. Additionally, a multiple comparison plot was developed to visualize differences for comparisons that were deemed to be significant. For the purpose of this study, a p value of 0.05 will be used to denote significance. When determining significance, a critical F statistic value of 5.6586 was determined based off a of an F distribution table for a two-tailed hypothesis, however, the correct p value takes precedence. The calculation of the critical F statistic value can be seen below. All statistics will be performed using MATLAB.

$$F(df1, df2) = F_c$$

$$F(k-1, N-k) = F_c$$

N represents the number of samples (28), and k represents the number of groups (2)

$$F(1,26) = 5.6586$$

Results

After following the aforementioned methodology, it was concluded that some statistically significant differences exist ($p < 0.05$) between the limb conducting the movement and the session in which the movement was performed.

For shoulder forward flexion, it was determined that there were no significant differences between the limb or the session for the middle deltoid EMG signal. However, for the triceps brachii, it was reported that there was a significant difference between limbs ($F = 37.51$, $p = 7.53e-6$), and between sessions ($F = 5.76$, $p = 0.0491$). For elbow flexion/extension, it was determined that there was a significant difference between limbs ($F = 275.82$, $p = 3.48e-14$) for the biceps brachii. For the triceps brachii, it was reported that there was a significant difference between limbs ($F = 85.33$, $p = 6.78e-9$), and due to the interaction between the independent variables ($F = 24.41$, $p = 9.65e-5$). For wrist flexion/extension, it was determined that there were no significant differences between limbs or sessions for the EDS, FCR or ECR. For wrist supination/pronation, it was determined that there was a significant difference between limbs ($F = 18.92$, $p = 6.50e-4$) for the FCR and for the BB ($F = 604.32$, $p = 4.75e-14$). For ulnar/radial deviation, it was determined that there was a significant difference present between sessions ($F = 17.38$, $p = 0.001$), and due to the interaction between independent variables ($F = 7.74$, $p = 0.021$) for the EDS. For the FCR, it was determined that there was a significant difference present between limbs ($F = 6.09$, $p = 0.0422$), and due to the interaction between independent variables ($F = 15.22$, $p = 0.002$). Lastly for the ECR, it was determined that there was only a significant difference present between sessions ($F = 8.68$, $p = 0.0212$). For the hand opening/closing movement task, it was determined that there was a significant difference present between limbs ($F = 5.87$, $p = 0.047$) and between sessions ($F = 14.43$, $p = 0.003$) for the EDS. For the FCR, it was determined that there were no significant differences between limbs or the sessions.

For the horizontal grip movement task, it was determined that there was a significant difference present between limbs ($F = 226.7$, $p = 3.00e-13$) for the biceps brachii. For the triceps brachii, it was determined that there was a significant difference present between limbs ($F = 34.61$, $p = 1.36e-5$) and between session ($F = 13.54$, $p = 0.0024$). Lastly for the middle deltoid, it was determined that there was a significant difference present due to the interaction between the independent variables ($F = 8.55$, $p = 0.0223$). For the vertical grip movement task, it was determined that there was a significant difference present between limbs ($F = 256.21$, $p = 7.85e-14$), sessions ($F = 13.07$, $p = 0.003$) and due to the interaction between the independent variables ($F = 4.4$, $p = 0.047$) for the biceps brachii. For the triceps brachii, it was determined that there was a significant difference present between limbs ($F = 21.63$, $p = 3.03e-4$). Lastly for the middle deltoid, it was determined that there was a significant difference between sessions ($F = 62.03$, $p = 1.25e-7$) and due to the interaction between the independent variables ($F = 13.61$, $p = 0.0023$). For the cup grip movement task, it was determined that there was a significant difference present between limbs ($F = 8.09$, $p = 0.027$) for the EDS. For the FCR, it was determined that there was a significant difference present between limbs ($F = 7.23$, $p = 0.026$) and due to the interaction between the independent variables ($F = 24.42$, $p = 1.45e-4$). Lastly for the middle deltoid, it was determined that there was a significant difference present between sessions ($F = 42.55$, $p = 2.89e-6$). For the precision grip movement task, it was determined that there was a significant difference present between limbs ($F = 77.78$, $p = 1.62e-8$) and between sessions ($F = 8.18$, $p = 0.017$) for the

EDS. For the FCR, it was determined that there was a significant difference present between limbs ($F = 24.07$, $p = 1.58e\text{-}4$). For the ECR, it was determined that there was a significant difference present between limbs ($F = 6.64$, $p = 0.0497$). Lastly for the middle deltoid, it was determined that there was a significant difference present between sessions ($F = 128.2$, $1.24e\text{-}10$).

A summary table of all the results from the statistical tests performed can be found in the appendix. Additionally, the multiple comparison plots for the variables that were determined to have a significant difference can also be found in the appendix. These plots serve as a way to visualize the significant differences between column or row means.

Discussion

Based on the reported results, it can be observed that a fair number of significant differences were observed in the mean frequencies for the chosen wavelets. A large number of these differences were observed between limbs (17 significant differences observed) for a select movement and a specific EMG channel. This could potentially provide evidence on the effect of handedness in EMG signals for a select movement task. For example, individuals who usually hold a cup with their right hand are believed to be more comfortable performing the cup reach to grasp task with their right hand. This could potentially result in a larger, more profound signal in comparison to performing this movement with their left hand. This would indicate that a participant's handedness may have an impact on the quality of EMG movement features extracted from an EMG signal during select movement tasks. Discrepancies in the signal between the upper limbs could have also arisen due to the placement of the EMG electrodes. For the placement of the electrodes, the SENIAM guidelines were followed, however, the specific locations of the EMG electrodes must be confirmed with palpation especially for the muscles in the forearm which can be fairly difficult to isolate. Thus, it is highly probable that the electrodes may have been more accurately placed on one arm, resulting in an EMG signal with a larger amplitude spectrum when compared to the other arm. The electrode placement between both limbs were visually compared prior to conducting each EMG session, however, this is still prone to error. Differences between limbs could have also been observed due to the order of the movements. With this dataset, the right limb movements were performed first, and were promptly followed by the left limb movements. Although the movements are not physically taxing, the participant may have experienced some increasing fatigue as the testing session progressed. This would have negatively impacted the amplitude spectra of movements near the end of the testing session and could possibly provide some explanation for the discrepancies in mean frequency between limbs for a given muscle for a select movement.

Additionally, significant differences were observed between sessions (9 significant differences observed). With this study, the researchers strived to ensure that there were minimal differences between sessions. It is hypothesized that discrepancies were potentially observed due to differences in electrode placement between sessions. A picture was taken after each of the testing sessions as seen in the appendix, and from visual analysis it does not appear that there are any differences with electrode placement. However as mentioned earlier, the location of the muscles must be confirmed with palpation, and even then, the placement of the electrode along the muscle fiber may have differed. This would have impacted the amplitude spectra of the observed EMG signal, as one session may have had electrodes placed more proximal to the activated fibers. Differences between sessions could have also been observed due to differences in force applied and the "mind-muscle connection" employed by the participant. If a participant is more forceful while performing a specific movement task on one of the two sessions, increased activation would be observed in the EMG signal, and a significant difference would be reported by the ANOVA.

Significant differences were also observed due to the interaction between the independent variables (7 significant differences observed). This would have most likely been due to a combination of the factors previously mentioned.

Given the findings within this study and that the participant was right-handed, it is hypothesized

that the right-hand movements would elicit higher EMG activity. However, more data would need to be gathered, supplemented with stricter controls within the design (i.e. electrode placement), such that a more thorough analysis is developed.

Limitations

The primary limitation of this study is the small dataset employed within the analysis. One participant was used for this study which impaired the range of the mean frequency arrays used in the ANOVA. Given the small dataset, it is possible that small differences in the mean frequency were observed and reported as significant when in actuality they would not be considered as significant if the dataset was large enough. This would provide some explanation as to why a large number of significant differences were observed between sessions; it is hypothesized that a larger dataset would result in a more appropriate similarity range for mean frequency values. In addition to the small data size, the study is susceptible to order effect as the order was not changed between sessions. The current approach would have been appropriate if a larger number of participants were used, as then the order would have negligible effects on the results. However, with one participant it is highly probable that the movements at the end of the testing session may have been influenced by fatigue, and the lack of variability in the order prevented these discrepancies from being eliminated. Significant differences between limbs and sessions could have also arisen due to the differences in skin impedance measured at the beginning of each session. Within the study, the skin was prepped such that the impedance was below 10kOhm, however a constant skin impedance for each electrode site was not maintained between sessions or between limbs. This could have increased the resistance and negative impacted the signal to noise ratio (SNR) of the EMG signal, ultimately impairing the accuracy of the statistical tests. Lastly, within this study the EMG validation channels were manually selected based off of the researcher's knowledge on human anatomy as well as the wavelet's performance which was observed through a visual analysis. Although no known errors arose due to this, automating the validation process or adopting a feature-selection algorithm could have improved the accuracy of the intervals chosen.

Conclusion

This paper performed evaluated the influence of handedness on EMG movement features through a frequency-based approach. It was determined that several significant differences were observed when comparing the mean frequency arrays of EMG signals for a specific muscle for a given movement. Specifically, significant differences between limbs were the most prominent, potentially providing evidence for the impact of handedness on the amplitude spectra of an EMG signal. However, a more thorough approach and analysis would need to be adopted prior to making a definite conclusion regarding the relationship between handedness and EMG movement features. The approach can mostly be improved with a larger sample size as this will increase the statistical power of tests and increase the accuracy of conclusions made based on the results of the statistical tests. In the future, more participants would be recruited to participant in the study such that larger analyses could be made. Additionally, adoption of a feature-selection algorithm could be explored, specifically investigating whether it improves how the wavelet is developed and

how the individual movement phases are chosen. It is assumed that the application of these components will yield improved accuracy within the analyses.

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Appendix

EMG Electrode Placement

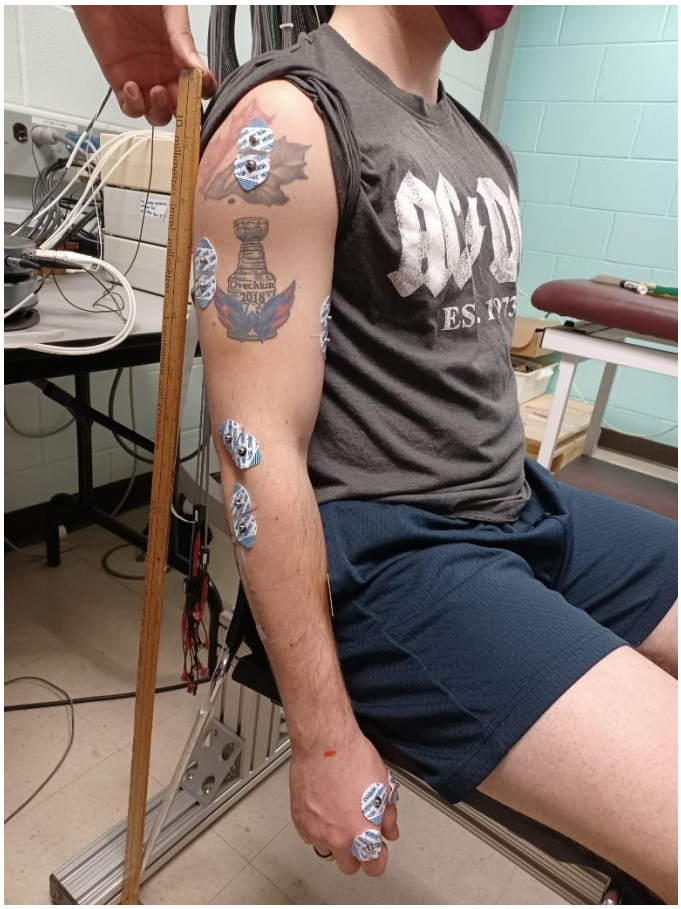

Figure 2: EMG Electrode Placement on the Right Arm during Session 1

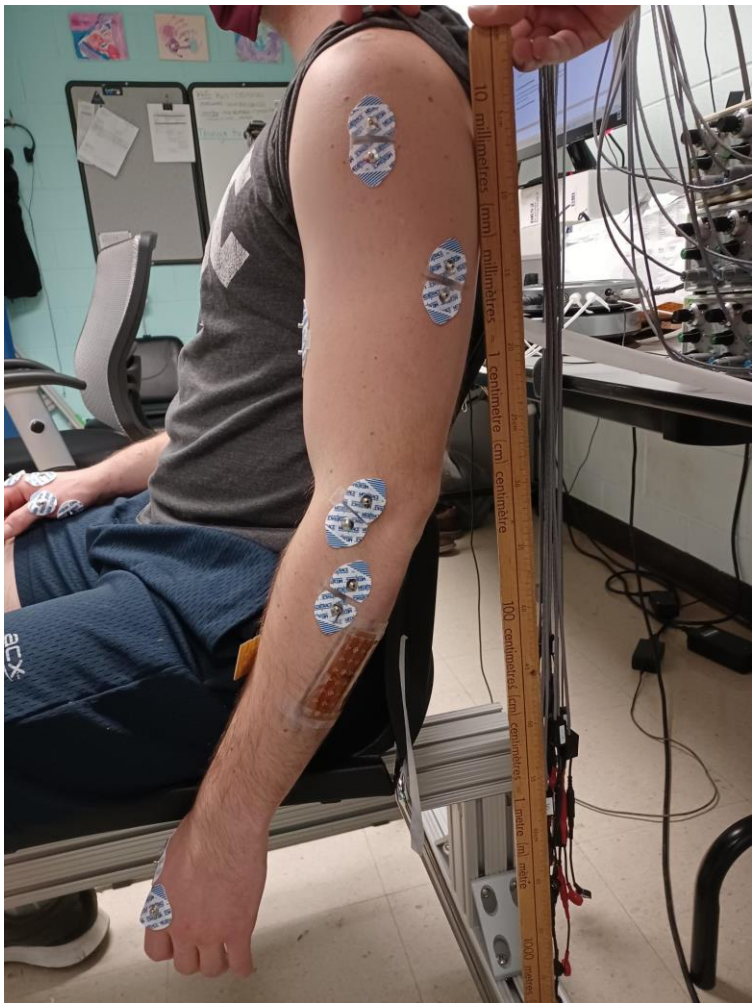

Figure 3: EMG Electrode Placement on the Left Arm during Session 1

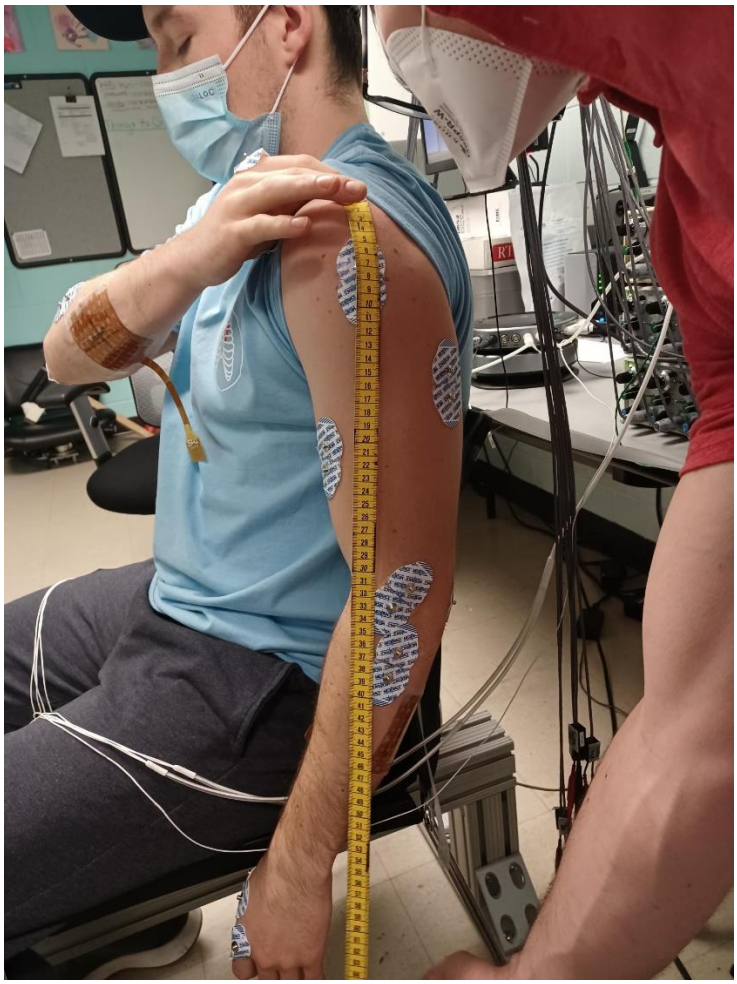

Figure 4: EMG Electrode Placement on the Left Arm during Session 2

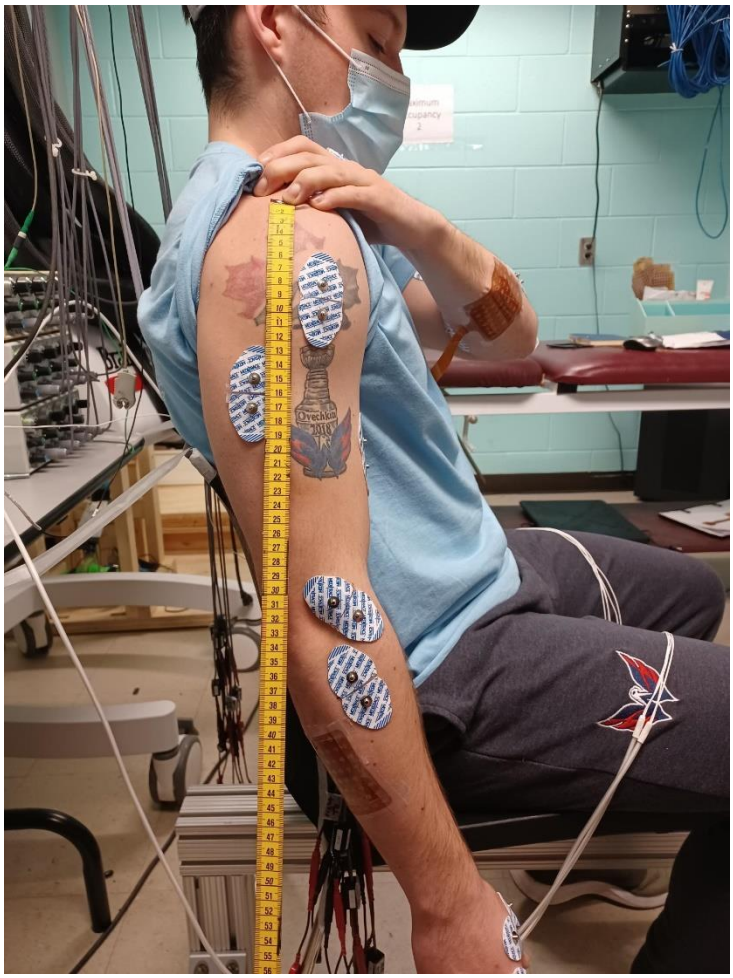

Figure 5: EMG Electrode Placement on the Right Arm during Session 2

Statistical Summary Tables

The following tables provide a summary of the results from the statistical tests performed in this paper. The cells that are highlighted indicate that a significant difference was found at $p < 0.05$. In terms of units, the mean values are reported in volts.

Cup Grip

Stats	EDS	FCR	MD
Left Visit 1 Mean	2.9525e-05	8.5722e-06	1.0125e-05
Left Visit 2 Mean	2.9291e-05	1.0932e-05	1.6054e-05
Right Visit 1 Mean	3.5808e-05	1.0417e-05	1.2846e-05
Right Visit 2 Mean	3.0247e-05	4.6850e-06	1.5974e-05
ANOVA – Columns	F = 8.09, p = 0.0269	F = 7.23, p = 0.0257	F = 3.62, p = 0.1099
ANOVA – Rows	F = 5.18, p = 0.0641	F = 4.24, p = 0.0505	F = 42.55, p = 2.86e-6
ANOVA - Interaction	F = 4.38, p = 0.0641	F = 24.42, p = 1.45e-4	F = 4.07, p = 0.1099

Elbow Flexion/Extension

Stats	BB	TB
Left Visit 1 Mean	1.3966e-05	7.9933e-06
Left Visit 2 Mean	1.6955e-05	6.7319e-06
Right Visit 1 Mean	1.3130e-04	9.3889e-06
Right Visit 2 Mean	1.2463e-04	1.1337e-05
ANOVA – Columns	F = 275.82, p = 3.48e-14	F = 85.33, p = 6.78e-9
ANOVA – Rows	F = 0.07, p = 0.9654	F = 1.12, p = 0.3008
ANOVA - Interaction	F = 0.51, p = 0.9654	F = 24.41, p = 9.65e-5

Hand Opening/Closing

Stats	EDS	FCR
Left Visit 1 Mean	5.8670e-05	2.2798e-05
Left Visit 2 Mean	6.4629e-05	1.9005e-05
Right Visit 1 Mean	6.0262e-05	2.4789e-05
Right Visit 2 Mean	7.8422e-05	2.2202e-05
ANOVA – Columns	F = 5.87, p = 0.0466	F = 1.39, p = 0.5007
ANOVA – Rows	F = 14.43, p = 0.0026	F = 2.10, p = 0.4809
ANOVA - Interaction	F = 3.69, p = 0.0666	F = 0.08, p = 0.7865

Horizontal Handle Grip

Stats	BB	TB	MD
Left Visit 1 Mean	8.6057e-06	1.3666e-05	1.6226e-05
Left Visit 2 Mean	1.0639e-05	1.1716e-05	1.7863e-05
Right Visit 1 Mean	4.1835e-05	1.7862e-05	1.7835e-05
Right Visit 2 Mean	4.9574e-05	1.5082e-05	1.5279e-05
ANOVA – Columns	F = 226.7, p = 3.00e-13	F = 34.61, p = 1.36e-5	F = 0.46, p = 0.9999
ANOVA – Rows	F = 4.16, p = 0.1052	F = 13.54, p = 0.0024	F = 0.41, p = 0.9999
ANOVA - Interaction	F = 1.42, p = 0.2454	F = 0.42, p = 0.5246	F = 8.55, p = 0.0223

Precision Grip

Stats	EDS	ECR	FCR	MD
Left Visit 1 Mean	2.2135e-05	1.4829e-05	1.0041e-05	1.2942e-05
Left Visit 2 Mean	2.6326e-05	1.8827e-05	8.3905e-06	1.8644e-05
Right Visit 1 Mean	1.2860e-05	1.2605e-05	5.5916e-06	1.3875e-05
Right Visit 2 Mean	1.5263e-05	1.2586e-05	5.2408e-06	1.8874e-05
ANOVA – Columns	F = 77.78, p = 1.61e-8	F = 6.64, p = 0.0497	F = 24.07, p = 1.58e-4	F = 1.51, p = 0.4611
ANOVA – Rows	F = 8.18, p = 0.0173	F = 1.47, p = 0.4665	F = 1.67, p = 0.4173	F = 128.2, p = 1.24e-10
ANOVA - Interaction	F = 0.60, p = 0.4458	F = 1.50, p = 0.4665	F = 0.70, p = 0.4173	F = 0.55, p = 0.4641

Shoulder Forward Flexion

Stats	TB	MD
Left Visit 1 Mean	1.0165e-05	2.9952e-05
Left Visit 2 Mean	1.0769e-05	3.1147e-05
Right Visit 1 Mean	1.3560e-05	3.0175e-05
Right Visit 2 Mean	1.6550e-05	3.4456e-05
ANOVA – Columns	F = 37.51, p = 7.53e-6	F = 2.32, p = 0.2819
ANOVA – Rows	F = 5.76, p = 0.0491	F = 5.57, p = 0.0802
ANOVA - Interaction	F = 2.54, p = 0.1244	F = 1.77, p = 0.2819

Ulnar/Radial Deviation

Stats	EDS	FCR	ECR
Left Visit 1 Mean	4.2665e-05	3.2143e-05	4.2737e-05
Left Visit 2 Mean	4.5652e-05	1.7679e-05	5.7287e-05
Right Visit 1 Mean	3.6208e-05	2.6640e-05	3.8298e-05
Right Visit 2 Mean	5.1190e-05	4.2140e-05	4.8996e-05
ANOVA – Columns	F = 0.05, p = 0.8331	F = 6.09, p = 0.0422	F = 2.21, p = 0.3010
ANOVA – Rows	F = 17.38, p = 0.0010	F = 0.02, p = 0.8938	F = 8.68, p = 0.0212
ANOVA - Interaction	F = 7.74, p = 0.0207	F = 15.22, p = 0.0020	F = 0.20, p = 0.6572

Vertical Handle Grip

Stats	BB	TB	MD
Left Visit 1 Mean	1.1125e-05	5.8436e-06	9.8305e-06
Left Visit 2 Mean	1.6873e-05	6.6258e-06	1.6492e-05
Right Visit 1 Mean	6.3761e-05	7.5967e-06	1.2700e-05
Right Visit 2 Mean	8.5378e-05	7.4985e-06	1.5111e-05
ANOVA – Columns	F = 256.21, p = 7.85e-14	F = 21.63, p = 3.03e-4	F = 1.67, p = 0.2087
ANOVA – Rows	F = 13.07, p = 0.0028	F = 1.47, p = 0.2640	F = 62.03, p = 1.25e-7
ANOVA - Interaction	F = 4.40, p = 0.0467	F = 2.43, p = 0.2640	F = 13.61, p = 0.0023

Wrist Flexion

Stats	EDS	FCR	ECR
Left Visit 1 Mean	5.8285e-05	1.0292e-05	5.2910e-05
Left Visit 2 Mean	6.1138e-05	1.0557e-05	5.6877e-05
Right Visit 1 Mean	4.6258e-05	9.3134e-06	4.9498e-05
Right Visit 2 Mean	6.1370e-05	1.2637e-05	6.4554e-05
ANOVA – Columns	F = 1.55, p = 0.4148	F = 0.15, p = 0.7028	F = 0.17, p = 0.6840
ANOVA – Rows	F = 3.60, p = 0.2091	F = 1.58, p = 0.6617	F = 3.38, p = 0.2357
ANOVA - Interaction	F = 1.68, p = 0.4148	F = 1.15, p = 0.6617	F = 1.15, p = 0.5896

Wrist Supination

Stats	FCR	BB
Left Visit 1 Mean	1.3362e-05	1.7070e-05
Left Visit 2 Mean	1.5095e-05	2.3418e-05
Right Visit 1 Mean	1.0172e-05	1.7257e-04
Right Visit 2 Mean	6.8571e-06	1.8560e-04
ANOVA – Columns	F = 18.92, p = 6.50e-4	F = 604.32, p = 4.75e-18
ANOVA – Rows	F = 0.36, p = 0.5527	F = 2.25, p = 0.2936
ANOVA - Interaction	F = 3.69, p = 0.1332	F = 0.27, p = 0.6098

Multiple Comparison Plots

A select few sample multiple comparison plots were provided to visually showcase the significant differences present between the groups for a select movement.

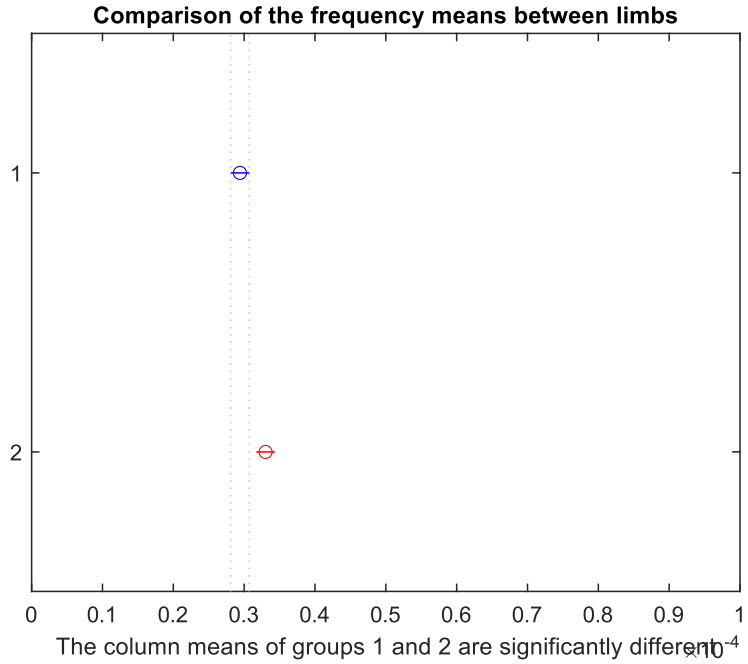

Figure A1: Comparison of frequency means between limbs for EDS EMG signals of the Cup Grip movement

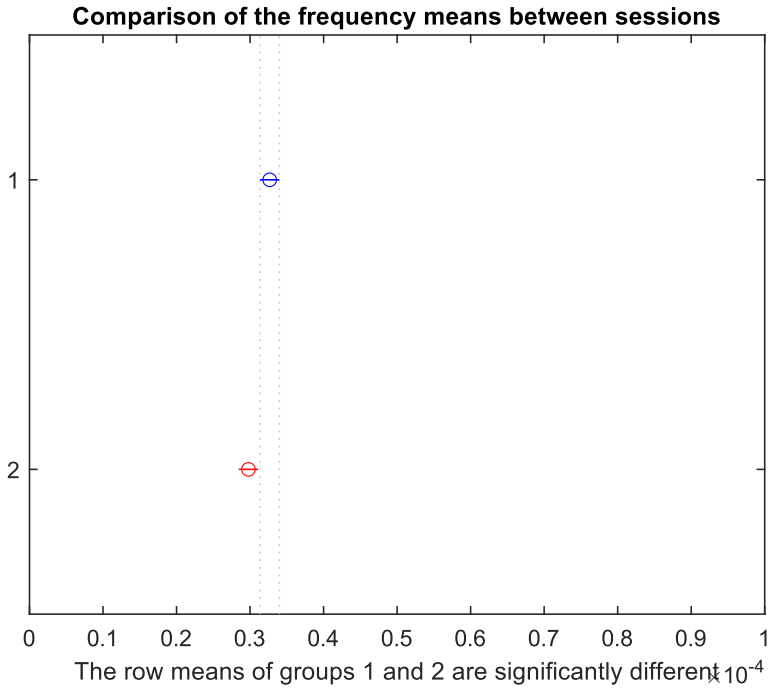

Figure A2: Comparison of frequency means between sessions for EDS EMG signals of the Cup Grip movement

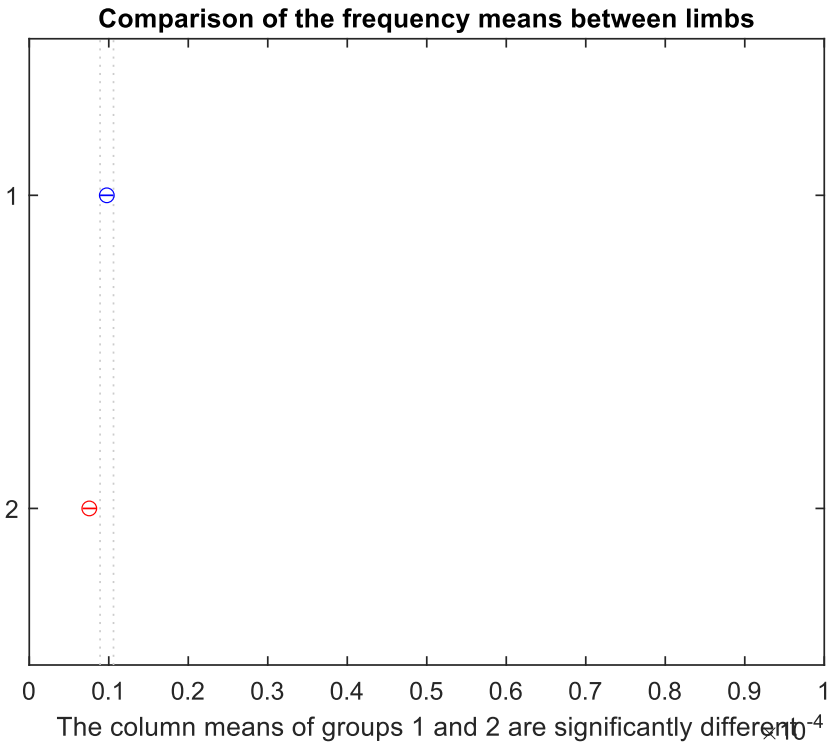

Figure A3: Comparison of frequency means between limbs for FCR EMG signals of the Cup Grip movement

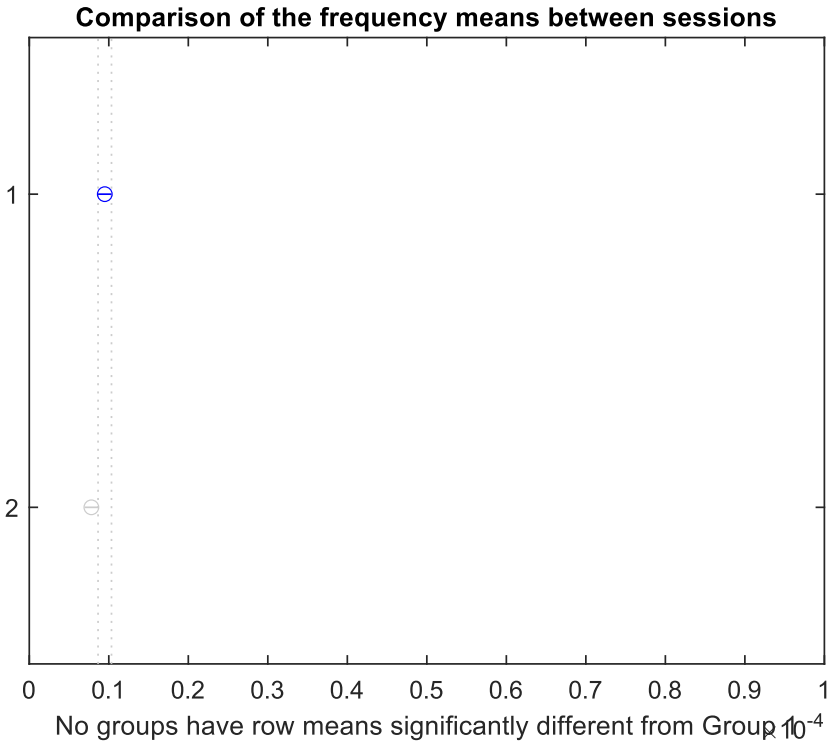

Figure A4: Comparison of frequency means between sessions for FCR EMG signals of the Cup Grip movement

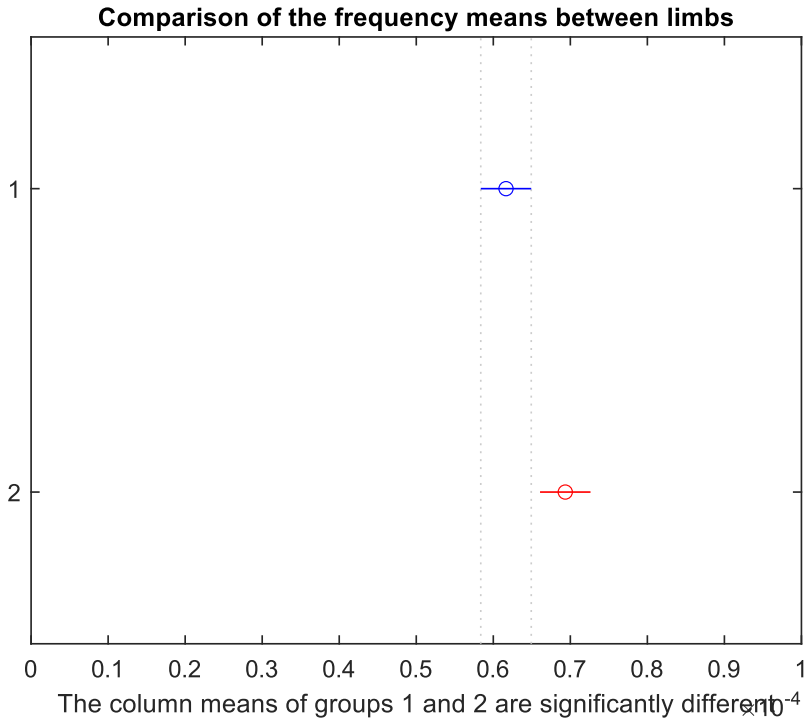

Figure A5: Comparison of frequency means between limbs for EDS EMG signals of the Hand opening and closing movement

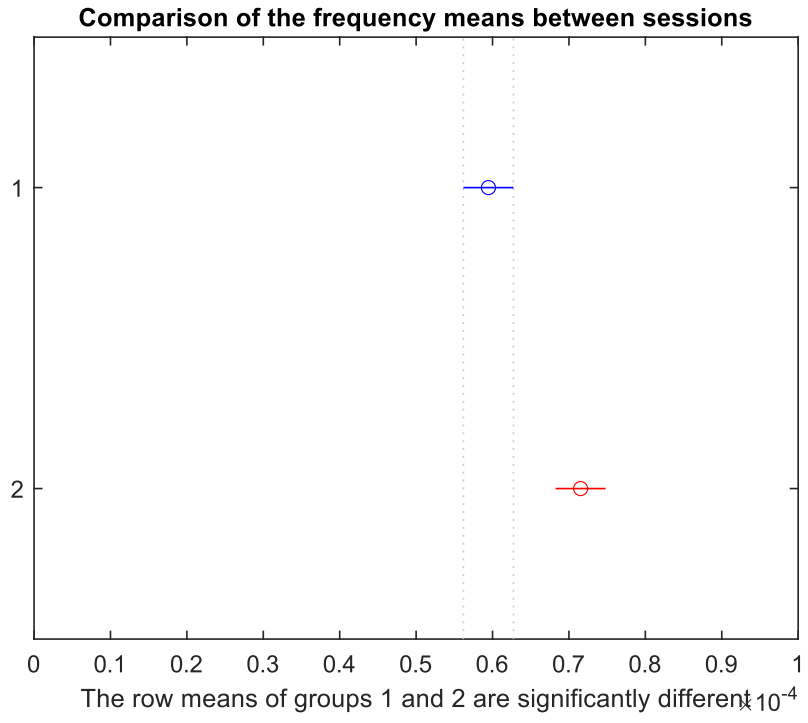

Figure A6: Comparison of frequency means between sessions for EDS EMG signals of the Hand opening and closing movement

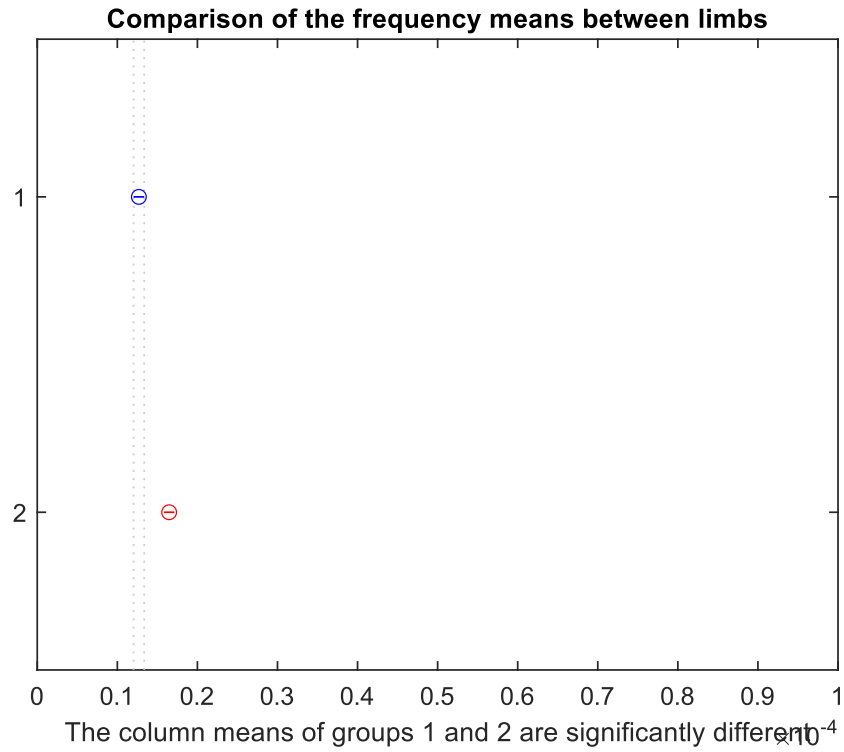

Figure A7: Comparison of frequency means between limbs for TB EMG signals of the Horizontal Handle Grip Movement

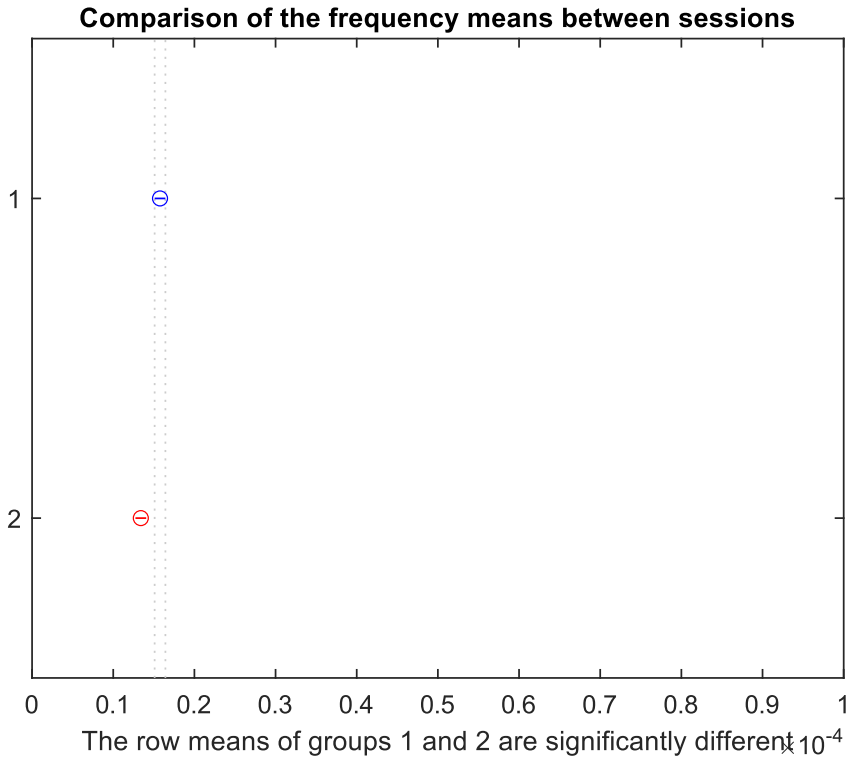

Figure A8: Comparison of frequency means between sessions for TB EMG signals of the Horizontal Handle Grip Movement

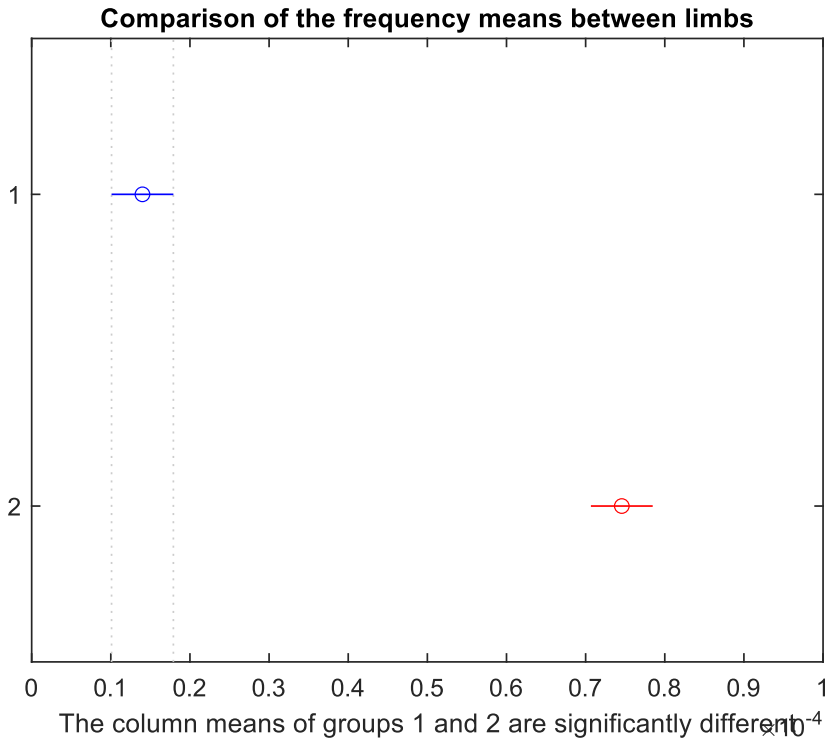

Figure A9: Comparison of frequency means between limbs for BB EMG signals of the Vertical Handle Grip Movement

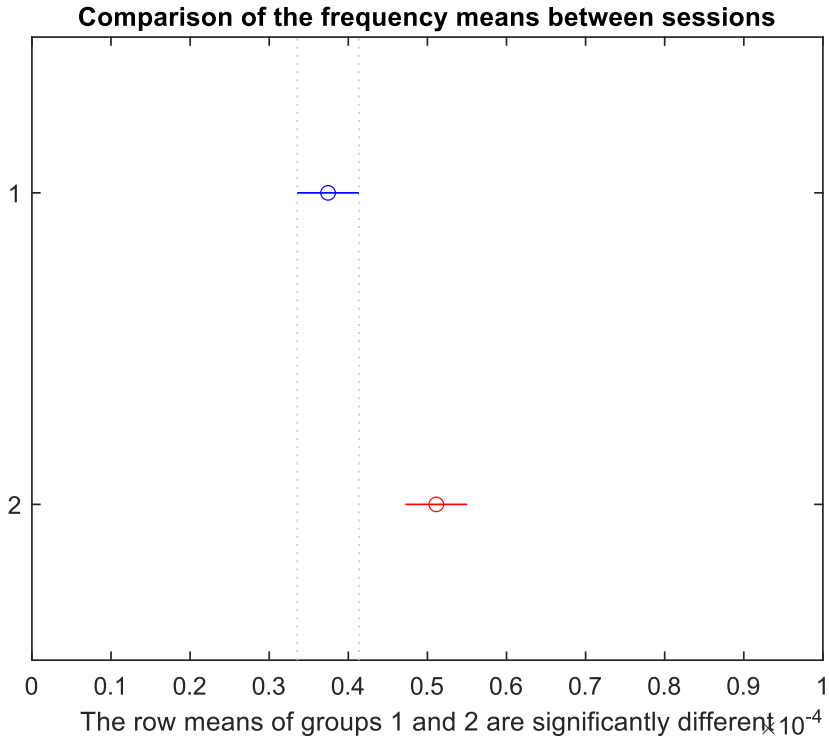

Figure A10: Comparison of frequency means between sessions for BB EMG signals of the Vertical Handle Grip Movement